Application of Spatial Modulation to the Underwater Acoustic Communication Component of Autonomous Underwater Vehicle Networks

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LONG-TERM GOALS

There have been two fundamental advances in underwater acoustic communication in the last two decades. The first occurred in the early 1980's with the introduction of digital signaling techniques [1]. That facilitated both error correction and reverberation mitigation. The second advance has been the successful application of coherent signaling techniques [2]. That facilitated dramatic improvements in bandwidth efficiency and, hence, data rates. Since the introduction of coherent systems in the early 1990's, however, performance gains have been moderate and mostly attributed to important but largely technical algorithm improvements [3]. Spatial modulation offers the hope of yet another fundamental advance in performance by both enabling higher data rates and offering a strategy for improving performance in intersymbol interference (ISI) limited channels. The research conducted in this program seeks to define both the potential for spatial modulation in U.S. Navy underwater communication systems and develop practical prototypes suitable to meet U.S. Navy needs.

OBJECTIVES

This program seeks to apply spatial modulation to a variety of practical ocean acoustic channels such as those encountered by U.S. Navy acoustic communication systems. The current phase of the work is driven by a desire to successfully transition the technology to meet a near term Navy need. Specifically, requirements derived from the autonomous underwater vehicle (AUV) platforms currently being considered by the Autonomous Operations Future Naval Capability (AOFNC) have been adopted. FY03 efforts have adopted aperture and frequency range constraints consistent with current AOFNC development efforts and sought to define spatial modulation performance within these bounds. Specific objectives of this current effort are:

1. Continue to accrue experimental validation of spatial modulation under AOFNC AUV constraints.
2. Demonstrate spatial modulation in networked environments.
3. Reduce the computation load of receiver algorithm to facilitate a real-time implementation.

APPROACH

The issue of how to map an information stream onto a transmit array is a rich area of current research in the wireless radio frequency industry. Many older approaches to spatial modulation for multiple-

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14. ABSTRACT
There have been two fundamental advances in underwater acoustic communication in the last two decades. The first occurred in the early 1980???s with the introduction of digital signaling techniques [1]. That facilitated both error correction and reverberation mitigation. The second advance has been the successful application of coherent signaling techniques [2]. That facilitated dramatic improvements in bandwidth efficiency and, hence, data rates. Since the introduction of coherent systems in the early 1990???s, however, performance gains have been moderate and mostly attributed to important but largely technical algorithm improvements [3]. Spatial modulation offers the hope of yet another fundamental advance in performance by both enabling higher data rates and offering a strategy for improving performance in intersymbol interference (ISI) limited channels. The research conducted in this program seeks to define both the potential for spatial modulation in U.S. Navy underwater communication systems and develop practical prototypes suitable to meet U.S. Navy needs.

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input / multiple-output channels center on a singular value decomposition of a known channel transfer function matrix [4] [5] [6]. These techniques require knowledge of the channel by the transmitting system. Recent approaches suggest various mappings of coded and uncoded data streams to the available transmitters [7] [8] [9] [10] [11] [12]. These approaches are motivated by channels typically encountered in RF wireless systems, namely channel transfer function matrices whose elements are independent, Rayleigh fading variables and channels with negligible intersymbol interference (ISI). The underwater acoustic channel typically carries neither of these traits in that receiver elements are often partially correlated and ISI is far from negligible.

The current effort addresses two issues relating to communication links within an underwater network comprising multiple platforms including AUVs, submarines, and surface vessels. First, appropriate array geometries are being studied that both conform to the aperture constraints of AUVs and simultaneously provide adequate spatial degrees of freedom to support simultaneous spatial modulation links between multiple platforms. At a simplistic level, vertical aperture helps with spatial modulation while horizontal aperture helps with multi-user separation. The design space is rich with trade-offs. The extensive practical experience of Lee Freitag and other WHOI personnel plays a large role in the execution of this task. A general-purpose array whose aperture spans the anticipated design space for AUVs has been constructed to support the testing of multiple configurations during a single test. Based on predicted performance using propagation models, tests will be designed involving a central "mother ship" that is communicating with at least two subordinate AUVs. For this program, only the aperture of the AUV will be represented and no effort will be made to mimic the AUV structure itself. The testing will be conducted near the Gould Island Acoustic Test Range (GIATR) during Fall 2003 under the presumption that it represents an environment representative of a AOFNC mission.

Second, much of the effort to date has focused on the physical feasibility of spatial modulation. The receiver algorithm has thus favored performance over complexity. A reexamination of the algorithm is needed that quantifies the tradeoff between performance and complexity. Complexity reduction techniques that would enable implementation on a real-time system that is sustainable in AUV processor footprint are needed. For example, the horizontal and vertical apertures could be processed sequentially rather than jointly. Similarly, spatial and temporal degrees of freedom might be treated sequentially. While analysis has shown that recursive least square-based adaptive algorithms are necessary, the performance of fast transversal filter implementations is under study. In a more mundane vein, the core Viterbi algorithm that accomplishes decoding jointly with equalization has much room for speed improvement. The trade space between performance and complexity must be quantified via algorithm development and testing with field data. The goal is to recommend a receiver algorithm to ONR that may be viably implemented in a real-time system during a follow-on effort.

WORK COMPLETED

A four-element transducer array capable of efficiently transmitting waveforms over the full bandwidth of 25 kHz to 45 kHz has been developed. The transducers are ITC omni directional elements with a maximum sound pressure level of 190 dBre1Pa@1m. In addition to the rigid 16 element (6 inch spacing) hydrophone array developed in FY02, a flexible 16 element (1 m spacing) hydrophone array has also been brought into the program.

Testing was delayed until late in the fiscal year due to permitting difficulties. A successful test was conducted in late May GIATR using a variety of HF waveforms and AUV compatible apertures.

While tests were conducted using the transducer array to simultaneously transmit spatially modulated waveforms to two GIATR nodes, the proposed test to transmit spatially modulated waveforms from two vehicles with reception on a single, planar array has not been conducted yet due to scheduling conflicts. That test will be conducted this fall.

Numerous receiver algorithm refinements have been completed to decrease processing latency. A fast transversal filter algorithm has been implemented to provide the performance of recursive least squares-based algorithms with the low complexity of least mean square algorithms.

RESULTS

The primary result of the program this year was to demonstrate that greater than a 200% increase in capacity is possible by using spatial modulation at 25 – 35 kHz frequencies using apertures supported by AO FNC class AUVs. Figure 1 shows the capacity at four ranges at GIATR. The transducer spacing was 21 inches while the receiver comprised 5 elements spanning 24 inches. Thus an Odyssey class aperture accommodated dual data stream spatial modulation that nearly doubled achievable data rates. For reference, the ocean channel at GIATR is 15 m – 30 m deep with a sandy, gravel bottom type. Capacity was estimated by assuming the post-equalization noise was well-modeled as additive, white Gaussian noise and using average post-equalization SNR in the well known formula, capacity = $\log_2(1+SNR)$.

An important anecdotal result was obtained when a 20 kHz bandwidth spatially modulated waveform was successfully sent over a nearly 1 km channel. Three simultaneous data streams were sent and the received signal would have supported 200 kbps aggregate data rate using commonplace modulation techniques yielding an easily obtained spectral efficiency of 10 bits/Hz (as compared to capacity which is difficult to achieve).

IMPACT/APPLICATIONS

Navy needs for acoustic communication have been established for current AUV development and demonstration programs. These include relatively high data rates (50 kbit/sec per kilometer is one stated goal) for certain missions where large amounts of sensor data are gathered and processed by an AUV. Timely reception of this data by other vehicles or human analysts may provide a significant tactical advantage in littoral engagements. Given the limited bandwidth available undersea, methods that offer a factor of two or more increased throughput are very attractive.

Examples of potential transitions include programs such as the pre-planned product improvement (P3I) for the Semi-Autonomous Hydrographic Reconnaissance Vehicle (SAHRV) that is based on the WHOI REMUS AUV. As these technologies mature, future P3I opportunities may become available. Another possible transition is through follow-on programs to the AO-FNC, which uses the 21 inch Bluefin Robotics AUV as a communications and navigation aid. The AO-FNC may also lead to pre-procurement programs in anticipation of adding the vehicles to Navy field units. An example of realistic source arrays that could be added with modest impact to an Odyssey class vehicle is shown in Figure 2. On-going and proposed work will characterize the potential throughput increase possible with these practical apertures.

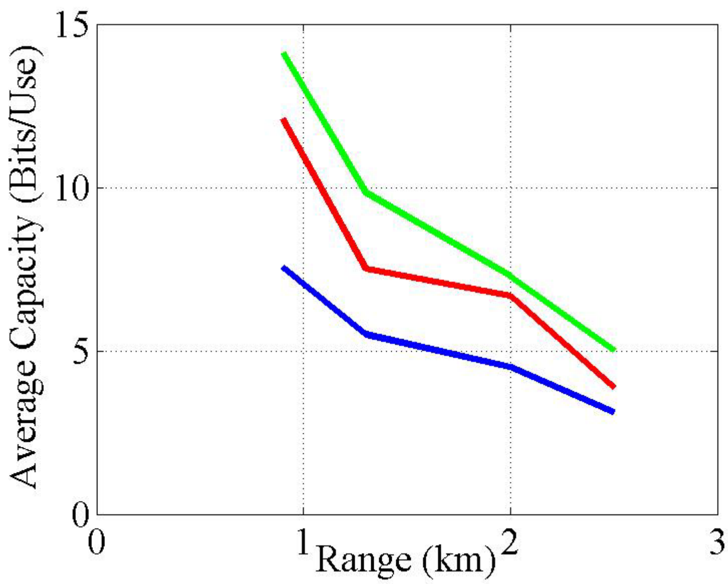

Figure 1. The average capacity achieved as a function of range during HF spatial modulation testing at GIATR is shown here. The underlying waveforms used for this calculation spanned 10 kHz so the peak capacity was about 140 kbps using three data streams. Even higher capacity was achieved with the 20 kHz waveforms.

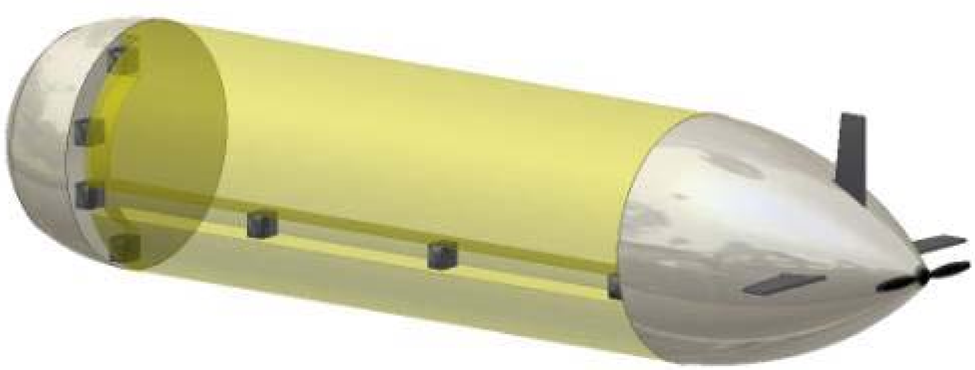

Figure 2. Odyssey-class (21 inch) AUV with both vertical and horizontal piezocomposite source arrays built of directional elements such as manufactured by Materials Systems Inc.

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